Application of Synthetic Aperture Radar Interferometry (InSAR) in Defining Mine-Related Ground Deformation and Subsidence Hazards

by
Ralph E. Weeks, RG; Bibhuti Panda, PE; & Kenneth Fergason, G.I.T.
AMEC Earth & Environmental, Phoenix, Arizona

Ground deformation resulting from the collapse of underground workings, unstable embankment or open-pit slopes, or dewatering of alluvial aquifers can pose a threat to the integrity of nearby infrastructure. This infrastructure often includes public highway corridors, with the deformation representing a potential hazard to the safe use of the highway, with both rapid and protracted consequences possible. Measuring the rate and distribution of this deformation enhances understanding of the geological and hydrological factors that influence past ground behavior, thereby improving prediction of further movement, and ultimately enhancing the effectiveness of mitigations undertaken.

A rapidly evolving technology is currently transitioning from the science research arena into applied practice. This technology is synthetic aperture radar interferometry (InSAR). InSAR has been successfully applied to evaluating ground deformations related to volcanism, tectonic fault movement, subsidence due to fluid withdrawal, and underground mine collapse. The objective of this paper is to present an overview of this progressive technology, summarize where it has been applied to the problem of mine subsidence, and provide an approach for utilizing InSAR for predicting future ground deformation related to fluid withdrawal.

OVERVIEW OF INSAR TECHNOLOGY

InSAR was first applied as a scientific tool in 1974 using data supplied by the first civilian remote sensing satellite, SeaSAT. However, not until the early 1990's did the more widespread application of InSAR data begin to rapidly evolve, with the launching of the European Space Agency (ESA) ERS-1 satellite. This landmark event was followed by the launchings of ERS-2, a Japanese prototype (JERS-1), and the Canadian RadarSat. ESA has recently moved to the next generation of satellites, with the launching of EnviSat. InSAR data will likely be available on a global scale for the foreseeable future.

InSAR utilizes satellite-supported data to detect minute ground deformations by comparing the phase variance between two side-looking, repeat orbital observations in nearly synchronous trajectories. Typical data acquisition occurs at orbital heights of approximately 700 km, utilizing a C-band wavelength of 5.6 cm, although some L-band (23.5 cm wavelength) data has been archived.

The first step in the processing of InSAR data for the detection of ground deformation is to separate the topographic signature from often-subtle expressions of ground displacement. This step employs the use of a digital elevation model (DEM), from another source, or generated from a manipulation of the InSAR data. Once accomplished, the phase is unwrapped, producing meaningful ground deformation maps.

InSAR has the advantage that cloud cover does not prevent the acquisition of data; however, atmospheric effects do often influence the quality of differential interferograms. InSAR also suffers from decorrelation, caused by an incoherent change in the position of the available reflectors. This limiting condition is encountered in forested, agricultural and mining regions, where rapid change occurs due to vegetation change, plowing or earthwork. The speckled areas in the example interferogram presented as Figure 1 are decorrelated. Each interferometric fringe depicted on the image represents about 3 cm of elevation change over a 44-month period in the Phoenix, Arizona metropolitan area. A fringe is a full color cycle (red to red, blue to blue) in the image.

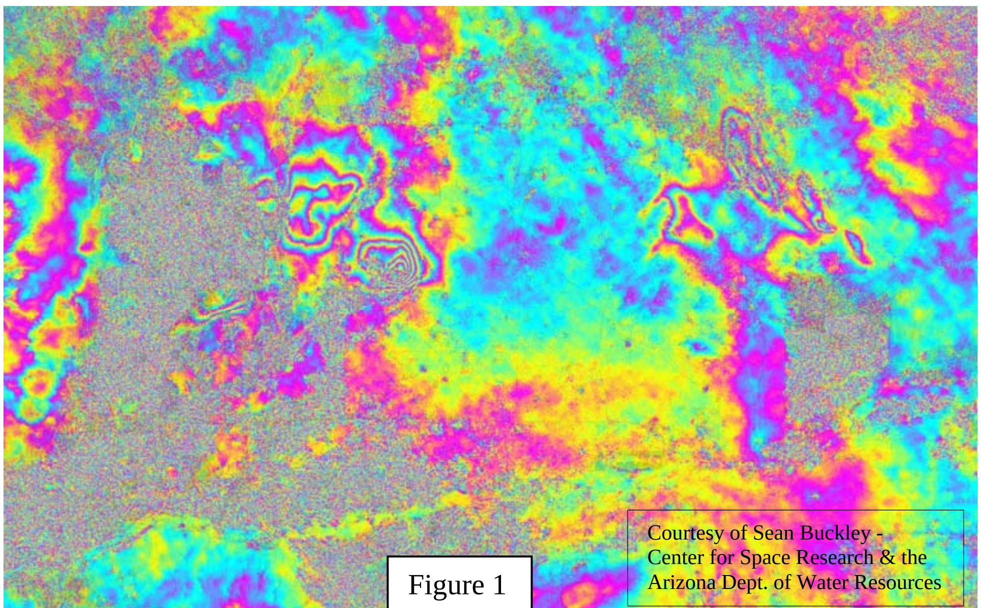

Figure 1

As related to the effects of dewatering, InSAR has been successfully used to map the distribution and rate of ground subsidence occurring since the early 1990's, with vertical precision in the range of 0.5 to 1 centimeter. Utilizing historical data from the past generation of ESA satellites, horizontal resolutions of 50 to 60 meters are common. Newer, tight-sweep coverage by satellites such as the new RadarSat-2 will provide much finer resolution.

QUANTIFYING GROUND DEFORMATION WITH INSAR

Since the mid-1990s, InSAR has gained popularity as a means to define and monitor ground deformation related to mining. InSAR has been utilized in studies where subsidence is caused by both underground mining and fluid withdrawal. InSAR has also been applied to slope stability studies. As summarized below, InSAR has been utilized in Europe, North America, and Australia in diverse climatic conditions, including sub-arctic, humid continental, and arid/desert environments.

Gold Mining Operations in Northern Nevada - Alluvial de-watering for the mining of gold in northern Nevada has resulted in subsidence. InSAR has been utilized by the authors to define and monitor ground deformations to aid in assessing the risk associated with ongoing subsidence and related hazards, such as earth fissuring. In addition, InSAR data has been utilized in stress-strain finite element modeling to aid in risk assessment**.**

McMicken Dam in Arizona - McMicken Dam is a 9-mile long earthen embankment that has experienced over 5 feet of differential subsidence since its construction in 1955. In addition, the presence of subsidence-induced earth fissures crossing beneath the dam has been confirmed, threatening the integrity of the structure. The authors, in cooperation with the Arizona Department of Water Quality and the Center for Space Research in Austin, have utilized InSAR to define and monitor ongoing subsidence. A stress-strain finite element analysis was utilized to identify zones at higher risk for future earth fissure development.

Upper Silesian Coal Basin in Poland - The Upper Silesian Basin is one of the world's largest mining centers and has been active since the 19th century. Annually, it produces about 130 million metric tons of coal from 65 underground mines. A negative result has been large-scale subsidence affecting almost 1500 km^2 (~580 mi^2). Since 1970, almost 40% of the coal mining activity has taken place underlying cities and important infrastructure (Perski and Jura, 1999).

Extensive research using InSAR technology has been performed in this region by Perski (1998a and 1998b), Perski and Jura (1999), Perski (2003), and Perski and Jura (2003). According to Perski and Jura (1999), four general conclusions have been reached:

- Application of SAR interferometry for the study and prediction of subsidence resulting from mining opens new applications for research, in particular for subsidence dynamics and their spatial distribution.

- SAR interferograms represent an important source of information for the understanding of subsidence dynamics over 35-day time intervals.

- InSAR images reveal areas with remnant subsidence of less than 1 cm/month. This provides a much more complete image of the subsidence behavior than information derived from conventional surveys.

- Interferometric analysis provides an effective tool to actively manage the operations at the working front, and rapidly estimate subsidence.

Island Copper Mine in Canada - Kosar et al. (2003) performed an InSAR technology demonstration study for the Island Copper Mine located on Vancouver Island in southwestern Canada. The Island Copper Mine is a decommissioned open-pit mine where the open pit was flooded with seawater to form a micromictic lake. As lower pit slopes were known to generate acid runoff, there was concern of a slope failure into the lake causing a lake turnover. Potential slope failures were identified prior to mine closure and a primary goal of the study was to test InSAR as a viable alternative to conventional ground based instrumentation in evaluating the risk associated with mine slopes, and whether the technology would provide adequate warning of potential failures affecting the environment (Kosar et al, 2003).

The use of InSAR was successful in detecting small ground movements along steep pit slopes. InSAR's advantage in detecting ground movement with continuous spatial coverage was clear compared to the 16,000+ GPS or survey monuments that would have been required for comparable results. In addition, since InSAR data is obtained remotely, there was added benefit due to the restricted physical access to pit slopes due to safety concerns (Kosar et al., 2003).

Ashcroft Railway Corridor in Canada - Kosar et al. (2003) utilized InSAR to identify and monitor several complex, slow moving landslides within the Ashcroft rail corridor in Canada. The utility of InSAR was demonstrated to be complementary with existing geotechnical engineering techniques and represents a significant addition to the understanding and risk management of large slope failures (Kosar et al., 2003).

Kiruna Mine in Sweden - Kiruna Mine is located in northern Sweden and is an underground hard rock mine that primarily mines iron. Subsidence related to hanging-wall caving is documented and endangering a nearby town. According to Henry et al. (2003), InSAR proved to be a cost-effective and spatially superior method for monitoring the progression of subsidence**.**

Mine Subsidence in Australia - A team of researchers has recently begun to use InSAR to study mine related subsidence in Australia (Chang et al, 2003a and 2003b; Ge et al., 2003; and Rizos et al., 2003). Research is on going, but preliminary results are favorable.

Coal Mining Yorkshire in United Kingdom - Stow and Wright (1997) successfully demonstrated that InSAR could be applied to subsidence related to coal mining activities in England.

MODELING SUBSIDENCE EFFECTS

Subsidence behavior was analyzed by the authors for a gold mining operation in Nevada where significant ground deformation was detected, apparently related to the dewatering of a deep alluvial aquifer. The following is a summary of the numerical modeling method employed to create a prediction tool for the project.

Lowering the groundwater elevation in a column of alluvial basin material results in an increase in effective stress; thereby increasing the loading on the material column. If that column consists of granular materials, typically sands and gravels, compression of the material below the initial water level takes place rapidly. If the material column contains fine-grained materials, typically clays, consolidation of the material below the initial water level takes place slowly. The time frame of the consolidation is a function of the permeability of the material, where lower permeability increases consolidation time. Consolidation is further a function of the distance to higher permeability zones that can relieve the excess pore pressure by draining water from the clayey materials. Greater distances to such permeable drainage zones increase consolidation time. Although consolidation increases can be modeled as an elastic phenomenon, rebound of the consolidation is typically not recoverable with a decrease in loading.

Theory And Numerical Approach

The relation between changes in pore fluid pressure and compression of the aquifer system is based on the principle of effective stress proposed by Terzaghi (1925),

$\sigma_e = \sigma_T - p$,

where effective or intergranular stress (σ_e) is the difference between the total stress (σ_T) and the pore fluid pressure (p). The total stress represents the geostatic load. Under this principle, when the total stress remains constant, a change in pore fluid pressure causes an equivalent change in effective stress within the aquifer system. This results in a small change in volume in an aquifer system that is governed by the compressibility of the aquifer system skeleton. Conceptually, the change in pore pressure with time is related to the change in void ratio by the following equation:

$p = e/a_v$

Where:

p = change in pore pressure

e = change in void ratio

a_v = coefficient of compressibility (related to skeletal compressibility)

Subsidence is estimated by multiplying the change in void ratio (e) by the vertical thickness of the medium:

$s = e \times 2H$

where:

s = vertical settlement at time t

2H = total vertical thickness of medium

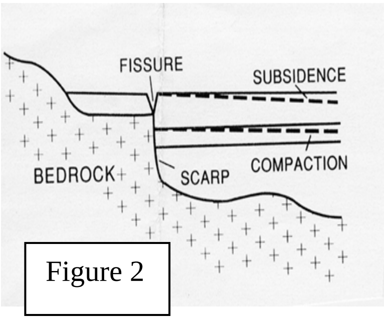

Figure 2

The surface subsidence and earth fissures are phenomena connected to groundwater withdrawal in a sedimentary basin. If the rock basement is irregular, not only vertical but also horizontal displacements are induced due to differential settlements and tensile stresses appear on the soil mass. When water level continue falling then earth fissure occur at the location of tensile zones, as depicted in Figure 2. The amount of compaction and the fissure geometry are closely related to the thickness and skeletal compressibility of fine-grained sediments, within the aquifer system, which in fact may vary with time.

Modeling subsidence and deformation of the alluvium in response to changes in groundwater levels in the aquifer system required addressing displacement and pore water pressure change simultaneously. A fully coupled analysis reasonably modeled the response of the applied stress to the alluvium structure due to change in pore water pressure with resulting deformation. This coupling was achieved with use of two finite element based computer programs, SEEP/W and SIGMA/W, developed by Geoslope (1998). SIGMA/W computes displacements and stresses while SEEP/W computes the changes in pore-water pressure with time. Running these two software products in a coupled manner made it possible to perform a reasonable subsidence and deformation analysis.

Modeling Concept

Water levels in the bedrock were consistent with the presence of a very permeable underlying bedrock unit containing an extensive system of large connected fractures or karstic conditions. The presence of subsidence indicated that a good hydraulic connection between the bedrock and the alluvium is present across much of the mine area and vicinity. Hydraulic connection between alluvium and bedrock may be primarily in the horizontal direction where the higher alluvium horizontal permeability controls water flow into the bedrock.

The numerical model simulated the observed subsidence within the aquifer system over time as measured or interpreted from InSAR data. The simulation was performed in several iterations to calculate spatial distributions of hydraulic conductivity and compressibility parameters for fine-grained sediments within the aquifer basin based on calibration of observed subsidence. Critical elements to the modeling were:

- Interferometric data to quantify actual subsidence since the start of pumping
- Realistic bedrock geometry to reasonably model geometric effects of subsidence
- Well hydrograph data to reasonably model pore pressure boundary conditions
- Internal pore pressure distributions through the modeled alluvial sections.

Input Data

Input data for the modeling effort consisted of an array of interrelated geometric and numerical components, including alluvial lithology, hydrological data and assigned mechanical properties of the alluvial materials.

> **Alluvial Lithology -** Geotechnical borings indicated that coarser or less clayey materials tend to be present in upslope portions of the shallow alluvial basin margin. This was consistent with the geologic setting, and coarser, less clayey materials may be present at depth in those upslope margin areas.

Shear wave velocity profiles of the upper 300 to 500 feet of the alluvium are consistent with shear wave profiles in other alluvial settings undergoing subsidence. From five refraction microtremor lines, typical shear wave velocities in the upper 100 to 200 feet range from 1,400 to 2,800 feet per second (f/s), and typical shear wave velocities below about 200 feet range from 2,300 to 4,500 f/s.

Well Data - Data trends in well hydrographs break into two very distinct and different patterns over the history of pumping at the project. Deep wells that penetrate into and measure water levels in bedrock follow a trend of substantial drawdown, greater than 500 feet to date, nearly matching the water levels due to pumping near the pit. Water level elevations and trends in these wells penetrating bedrock in different locations are so similar that large portions of the bedrock can be considered to be a very permeable unit that behaves as an underdrain beneath the alluvium in the modeled area.

Wells in the very shallow alluvium to depths of up to about 100 to 120 feet, on the other hand, have exhibited little response to the overall dewatering, and in many cases, have shown local rising water levels due to infiltration. A few wells have bottoms in the deep alluvium near the bedrock contact, and show water level elevations between the little changed shallow well water level elevations and the significantly changed deep bedrock well water level elevations

InSAR Data - Precise measurements of surface displacements due to dewatering and the changes in the hydraulic head of the aquifer system are the primary steps in the evaluation of subsidence analysis. InSAR provided the best means for achieving the necessary precision. In the past, InSAR data has been used to model the interbed skeletal compressibility to analyze the subsidence in Las Vegas Valley (Hoffman et al. 2001) and in Antelope Valley (Galloway et al. 1998, and Hoffman et al. 2002).

A series of six interferograms have been developed specifically for this project. The interferograms were produced in a range of time intervals from 7 to 23 months, with the

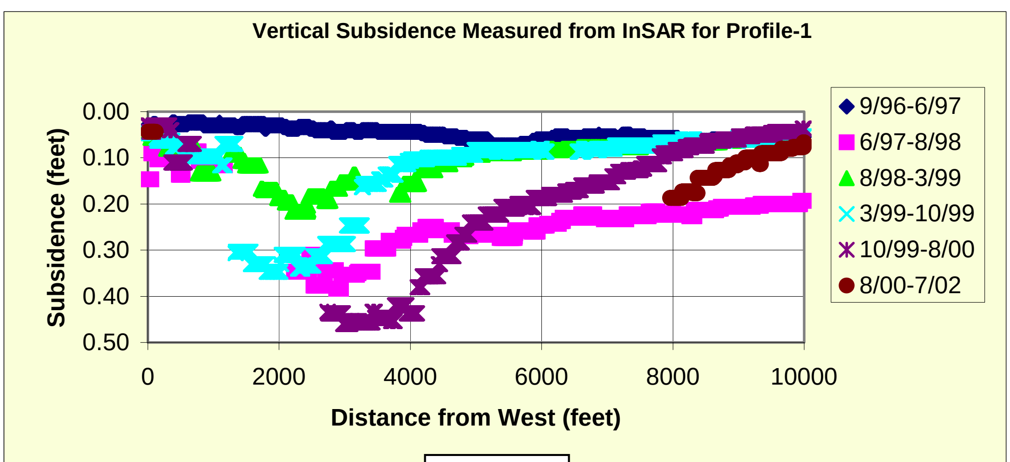

Figure 3

most recent being the longest. The vertical subsidence from InSAR data along one key profile is presented in Figure 3.

Mechanical and Hydraulic Parameters - The parameters sensitive to this coupled analysis are Young's modulus (E), saturated hydraulic conductivity (K) and coefficient of volume compressibility (M_v) which is related to poisson's ratio and modulus. The parameters were selected by calibrating the subsidence interpreted from InSAR data. The range of values used in the model is given below:

Type	K (ft/d)	E (psf)	Poisson's ratio
Fine-grained	0.005-0.01	2.5e6-4.5e6	0.3
Gravel	10	9.0e6	0.3
Model Rock	0.0005	5.0e7	0.3
Bed Rock	100	5.0e7	0.3

Model Geometry

The geometry of the bedrock profile under the alluvium is crucial to effective modeling of subsidence and deformation. Details of this geometry control locations and magnitudes of modeled strains. The alluvium depth and bedrock contact for the sections was developed from the extrapolation of exploratory borehole and well intercepts and reflection seismic profiles. Further refinements in model geometry were performed based on iterative results for the presence or absence of a more gravelly zone in the alluvium and the presence or absence of a less permeable bedrock cap under part of the alluvium.

Model Boundaries

Boundaries for the model sections are needed to constrain the analysis. Bedrock serves as an effective boundary for the northeast side of the model sections. Decline of water table (hydraulic head) due to pumping was modeled at this boundary. The lower model section boundaries are also bedrock, where the high permeability underlying bedrock is a relatively uniform condition. The southeast edge of the model sections was modeled as the deep alluvial basin. Given the low permeabilities in the alluvium, this boundary had relatively little effect on the subsidence and deformation modeling in the area of interest.

Calibration Of Flow And Subsidence

A steady-state flow model was developed based on pre-mining head condition. The results of the steady-state model was used as the initial condition for the transient flow model developed for consolidation analysis. The transient model was developed by running flow and deformation model simultaneously. The subsidence data measured from InSAR data between September 1996 to July 2002 was used to calibrate the model. The transient flow model was developed based on initial steady state condition representing the water level before dewatering. The transient head boundary condition was imposed based on the drawdown observed on the bedrock wells representing each profile. The drawdown in alluvium is not occurring at the same time as bedrock as there is a time delay due to lower permeability value in alluvium compared to bedrock. The subsidence data measured from InSAR was used to calibrate the flow and subsidence occurring in the area. The subsidence is very sensitive to the depth to bedrock (structure in the bedrock), permeability and elastic modulus of the alluvium. An iterative analysis was carried out by varying the above parameters for each profile to match the subsidence measured from the InSAR data. The model calibrated well to the InSAR data for all the time steps in the simulation. A comparison between the InSAR and modeled data for a given time duration is presented in Figure 4. Once calibrated, the model was then used for predicting subsidence behavior on the basis of anticipated future pumping conditions. The future head boundary conditions were developed using the output of another MODFLOW groundwater model.

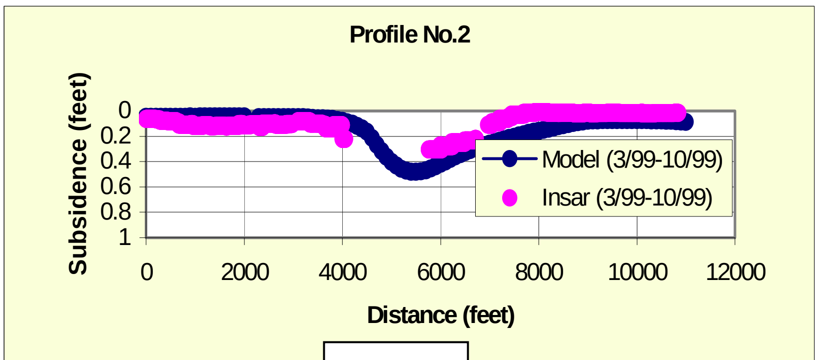

Figure 4

CONCLUSIONS

As clearly demonstrated by an array of prototype and applied studies, the application of InSAR to the problem of mine-related ground deformation has gained recognition, with the future of the application promising for many ground instability and subsidence problems. InSAR provides a unique spatial detail to the distribution and behavior of unstable conditions, unlike previous conventional terrestrial techniques. Utilizing InSAR as both a prediction instrument and monitoring tool holds great promise. Although there remain some obstacles to the unlimited application of the technology, the precision required to solve many mine-related problems is inherent in the technology. A recent data processing technique under development called coherent target analysis may overcome some incoherency limitations. The application of less accurate, but more tolerant L-band data may also have many applications related to large ground deformation in wooded terrain.

As demonstrated by the numerical modeling summarized above, InSAR will play an important role in characterizing and predicting ground subsidence due to groundwater withdrawal. The technology allows for the reconstruction of subsidence history without the benefit of previous terrestrial monitoring data. Its applicability then continues as a accurate means of monitoring ground deformation.

REFERENCES

Chang, H.C., Ge, L., Rizos, C., Hebblewhite, B., & Omura, M., 2003a, Repeat-pass satellite radar interferometry for mine subsidence monitoring. Australasian Ground Control in Mining Conference, Sydney, Australia, 10-13 November 2003.

Chang, H.C., Chen, M.H., Qin, L., Ge, L., & Rizos, C., 2003b, Ground subsidence monitored by L-band Satellite Radar Interferometry. Geomatics Research Australasia, 79, 75-89.

Galloway, D.L., Hudnut, K.W., Ingebritsen, S.E., Phillips, S.P., Peltzer, G., Rogez, F., and Rosen, P.A., 1998. Detection of Aquifer System Compaction and Land Subsidence using Interferometric Synthetic Aperture Radar, Antelope Valley, Mojave Desert, California. Water Resource Research, Vol. 34, No.10, p. 2573-2585.

Ge, L., Chang, H.C., Qin, L., Chen, M., & Rizos, C., 2003, Differential radar interferometry for mine subsidence monitoring. 11th Int. Symp. on Deformation measurements, Santorini, Greece, 25-28 May, 173-182.

Geo-Slope International Ltd., 1998, Finite Element Seepage Analysis Program SEEP/W, Version 4, Calgary, Alberta, Canada.

Geo-Slope International Ltd., 1998, Finite Element Stress and Deformation Analysis Program SIGMA/W, Version 4, Calgary, Alberta, Canada

Henry, E., Mayer, C., and Rott, H., 2003, Mapping mining-induced subsidence from space in a hard rock mine: example of SAR Interferometry application at the Kiruna Mine, Sweden. CIM Annual Conference, Montreal, Canada.

Hoffmann, J., Galloway, D. and Howard, A.J., 2003. Inverse Modeling of Interbed Storage Parameters Using Land Subsidence Observations, Antelope Valley, California. Water Resource Research, Vol. 39, No.2, 1231.

Hoffmann, J., Howard, A.J., Galloway, D. and Amelung, F., 2001. Seasonal Subsidence in Las Vegas Valley, Nevada, Observed by Synthetic Aperture Radar Interferometry. Water Resource Research, Vol. 37, No.6, p. 1551-1556

Kosar, K.; Revering, K.; Keegan, T.; Black, BK.; and Stewart, I. 2003, The use of spaceborne INSAR to characterize ground movements along a rail corridor and open pit mine. 3rd Canadian Conference on Geotechnique and Natural Hazards. Sheraton Hotel. Edmonton, Alberta, Canada. June 9 and 10, 2003.

Perski, Z., 1998a, Mining subsidence in the Szczyglowice coal mine and its interpretation by ERS SAR inteferometry. 4th European Coal Conference. Guide to Field Trips. p. 33-38.

Perski, Z.; 1998b, Applicability of ERS-1 and ERS-2 InSAR for Land Subsidence Monitoring in the Silesian Coal mining region, Poland. International Archives of Photogrammetry and Remote Sensing, Vol. 32, No. 7 p. 555-558.

Perski, Z., 2003, InSAR and POLinSAR for land subsidence monitoring – a user perspective. Proceedings of POLinSAR workshop. Frascati, 6 p., http://earth.esa.int/polinsar/participants/perski63/pol_insar_perski.pdf.

Perski, Z., and Jura, D., 2003, Identification and measurement of mining subsidence with SAR interferometry: potentials and limitations. Proceedings of the 11th FIG Symposium on Deformation Measurements, Santorini, Greece.

Rizos, C., Ge, L., Chang, H.C., & Nesbitt, A., 2003, The integration of GPS, Satellite Radar Interferometry and GIS technologies for ground subsidence monitoring. Spatial Sciences Coalition 2003 Conf., Canberra, Australia, 23-25 September, CD-ROM proc.

Stow, R., and Wright, P., 1997, Mining Subsidence Land Surveying by SAR Interferometry. 3rd ERS Symposium, Florence, Italy.

Terzaghi, K., 1925. Principles of Soil Mechanics, IV, Settlement and Consolidation of Clay, Eng. News Rec., 95(3), p. 874-878.

.